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(6) MEASUREMENT OF SIZE DISTRIBUTION OF SUBMICRON PARTICLES USING NEW LASER DIAGNOSTICS

By

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JOB

MEASUREMENT OF SIZE DISTRIBUTION OF SUBMICRON PARTICLES USING NEW LASER DIAGNOSTICS

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A. ABSTRACT

The one year research program described here was a direct extension of work completed during the 1977 AFOSR/ASEE Summer Faculty Research program at AFRPL. During that program the author and Dr. David Mann, AFRPL, performed the first in situ size measurements of submicron alumina (Al_2O_3) particles that have been published to date. The new laser diagnostic technique used, Diffusion Broadening Spectroscopy, represents a new advance in the state-of-the-art of submicron particle sizing.

The goal of the research described herein was to develop a data reduction procedure to extend the applicability of the technique, so that size distribution half width can be measured, in addition to particle mean diameter.

The computer routine was developed to determine particle mean diameter and size distribution half width, given light scattering data obtained at two scattering angles. Sensitivity of the results was investigated and feasibility of future use of the technique in rocket motors and plumes was deduced.

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3. Multiple angle scattering, using three or more detectors, as a method of measuring particle size distribution was considered. Analysis was performed to indicate the feasibility of obtaining particle size distribution directly, without assuming any functional form of the distribution.

C. STATUS OF THE RESEARCH EFFORT

Progress toward achieving the three major research objectives is now outlined.

1. Aerodynamic drag on submicron particulates was investigated for gas pressures between 10^{-6} to 1 atmosphere. Current theories describing free molecular flow drag forces, transition flow, and continuum flow forces were assessed. Of the numerous theories, the most realistic is one proposed by N.A. Fuchs which agrees with experiments performed by Millikan to within 2%. Particle drag in the free molecular, transition, and continuum ranges can be expressed as:

$$\text{Drag} = 6\,\pi\mu d U\,[(1 + .42\,\ell/d)^{-1} + 1.67\,\ell/d]^{-1}$$

Some values of particle drag are given in Fig. 1.

2. A distribution of particle sizes was considered and the net diffusion was investigated. A first step was to assume a functional form of the distribution (i.e. a log-normal distribution shape) and to determine if the geometric mean diameter and geometric standard deviation could be deduced using the DBS measuring technique. The results show such measurements are possible, if the scattering angle is optimized and the laser wavelength is chosen to be at least ten times the particle diameter (Mie scattering regime). Details of how to measure the geometric mean diameter and standard deviation of the aerosol are described in the attached publication. The major portion of the work done on this program is outlined in this publication. It was necessary to develop an extensive computer program to account for a polydisperse aerosol and low pressure effects as mentioned above in Item C.1.

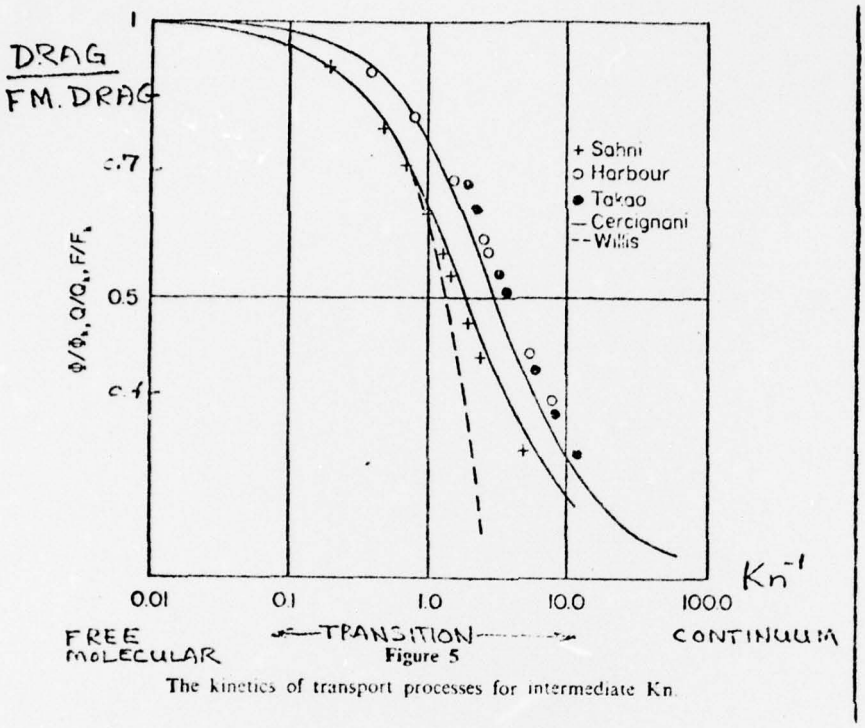

Figure 5

The kinetics of transport processes for intermediate Kn.

Figure 1. Particle Drag at Low Pressures
(Fuks, Highly Dispersed Aerosols)

3. Multiple angle scattering was considered in order to determine the particle size distribution curve without assuming a log-normal shape to the curve. Instead of a two parameter log-normal curve, a more general ten parameter curve was considered, requiring independent measurements at ten different scattering angles. Analysis showed that the uncertainty of results obtained using this method would be too high for practical application unless extreme care was taken to optimize the accuracy of each of the ten measurements. This did not appear feasible within the limitations of most university research programs.

D. PUBLICATIONS

"Submicron Particle Size Measurements in an Acetylene/Oxygen Flame," J.F. Driscoll, D.M. Mann, Third Int'l Workshop on Laser Velocimetry, Purdue, 1978.

"Submicron Particle Size Measurements in an Acetylene-Oxygen Flame," J.F. Driscoll, D.M. Mann, W.K. McGregor, accepted for publication, Combustion Science and Technology.

E. PERSONNEL

James F. Driscoll, Assistant Professor

F. OTHER PROGRESS:

Equipment has been purchased using University funds to allow this research effort to be continued. A submicron particle generator system and an argon ion laser have been purchased. A proposal to AFOSR for continuing research in this area is planned.

SUBMICRON PARTICLE SIZE MEASUREMENTS IN AN ACETYLENE-OXYGEN FLAME

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ABSTRACT

Diffusion broadening spectroscopy has been used to make in situ size measurements of submicron aerosol particles in an acetylene-oxygen flame. Making use of the spectral broadening of scattered laser light due to random particle motion, this optical technique has been demonstrated to be suitable for application in unsteady high temperature environments of 2,200°K in flowing gases. Particle sizes were found to vary from 40 to 250 nm as the height above the burner varied from 0.5 to 3.0 cm. Little variation was found as a result of equivalence ratio changes from 2.5 to 5.0. Sizes measured from electron microscope photographs of soot particles collected from the flame show reasonable agreement with those determined from scattering measurements. A method to measure geometric mean diameter and standard deviation of the particle size distribution in a polydisperse aerosol is also presented, and experimental results described. Modifications necessary to account for polydispersity and noncontinuum flow effects are discussed.

INTRODUCTION

The study of particle formation in flames and other condensation processes has been limited by the lack of adequate methods to measure particle size. Several optical methods have been proposed to determine particle size in situ, and thereby eliminate the problems inherent to conventional sampling probes, which can perturb the particle agglomeration and reaction process. However, flame particulates present special problems since they generally occur in the submicron size range and are usually of unknown composition. For this reason, the use of sizing diagnostics such as holography and fringe visibility interferometry (which are limited to approximately 5 μm) and Mie scattering (which depends on particle composition) has been limited in flames. Until recently, no single technique has afforded the capability of in situ sizing of submicron particulates of unknown composition.

A relatively new optical technique that can provide this capability was demonstrated by Cummins et al. (1964) and Foord et al. (1970) in liquids, and later by Hinds and Reist (1972) in a gas. This technique, which will be referred to as Diffusion Broadening Spectroscopy (DBS), relies on physical principles which were outlined by Cummins et al. (1964), Benedek (1969) and Edwards et al. (1971). Particle size is determined directly by measuring the spectral broadening of scattered laser light. Broadening of the observed optical spectrum is a result of two factors: the vigorous diffusion of particles due to their Brownian motion and the Doppler effect. Therefore, the particle diffusion coefficient can be determined directly from a measurement of the halfwidth of the optical spectrum. Particle size is

then inferred using a modified Stokes-Einstein relation that relates the diffusion coefficient and the particle diameter.

Several calibration studies have verified that accurate results can be obtained using the DBS technique. Cummins et al. (1964) used dilute solutions of monodisperse .088 μm polystyrene molecules and Hinds and Reist (1972) used airborne aerosols of monodisperse polystyrene particles in the .557 to 1.10 micron range. Penner et al. (1976) modified the technique for use in flowing gases and presented results obtained in an ethylene-oxygen flame.

In the work described herein, particle size measurements have been performed at various locations in an acetylene-oxygen flame, using Diffusion Broadening Spectroscopy. Results are compared with particle sizes determined from electron micrographs of particles collected from the flame. Methods to optimize signal to noise ratio in combustion processes and thereby enhance the range of size measurements possible have been identified. In order to size flame particulates, two modifications to the DBS technique were required. For our flame conditions, it was necessary to account for aerosol polydispersity and free molecular flow effects.

THEORETICAL CONSIDERATIONS

The fundamental physics underlying Diffusion Broadening Spectroscopy is described below. This treatment builds upon theory presented in Hinds and Reist (1972). A particle j, located at position vector $\bar{r}$ in the illuminating field of laser radiation of frequency ω_o, scatters light to a detector located at a scattering angle θ from the incident beam. The scattered electric field at the detector is:

$$E_s^j(t) = E_o \exp [i(\bar{k}\cdot\bar{r}(t) - \omega_o t)] \quad (1)$$

where E_o is the magnitude of the field at the detector, and the scattering wave vector $\bar{k}$ is:

$$\bar{k} = [(2\pi/\lambda_o)(\bar{e}_i - \bar{e}_s)] \quad (2)$$

Vectors $\bar{e}_i$ and $\bar{e}_s$ are unit vectors in the incident and scattered wave directions, respectively. The magnitude of $\bar{k}$ is

$$K = [(2\pi/\lambda_o)(2 \sin \theta/2)] \quad (3)$$

Particle motion results in a frequency shift of the scattered light which is represented by the time variation of the phase factor $\bar{k}\cdot\bar{r}$ in Eq. (1). For the case of uniform particle velocity v, the phase factor becomes

$$\bar{k}\cdot\bar{r} = \bar{k}\cdot\bar{v}t + \bar{k}\cdot\bar{r}_o \quad (4)$$

resulting in a constant frequency shift ω_D given by

$$\omega_D = |\bar{k} \cdot \bar{v}| = (2\pi/\lambda_o)\, \bar{v} \cdot (\bar{e}_s - \bar{e}_i) \qquad (5)$$

which is the familiar Doppler shift relation used in laser Doppler velocimetry. The vector $\bar{r}_o$ simply defines the coordinate system location.

To assess the effects of particle motion on the power spectrum of scattered light, the field correlation function is first computed:

$$\overline{E_s^*(t)\, E_s(t+\tau)} = \overline{\sum_{\ell} \sum_{j} E_o^{\ell}\, E_o^{j}\, \exp\,[ik \cdot (r_j(t) - r_j(t+\tau))]} \qquad (6)$$

where E_s is the sum of individual contributions:

$$E_s(t) = \sum_{j=1}^{N} E_s^{j}(t) \qquad (7)$$

Under the assumption that the scattering from each particle is independent, that the illumination is uniform and that the position of each particle depends only on the time interval τ:

$$R_E(\tau) \equiv \overline{E_s^*(t)\, E_s\,(t+\tau)} = N\, E_o^{2}\ \overline{\exp\,[i\, k \cdot \Delta r_j]} \qquad (8)$$

$$\overline{\Delta r_j} = \overline{r_j}(t) - \overline{r_j}(t+\tau) \qquad (9)$$

The average over Δr is given by:

$$\overline{\exp\,(i\, k \cdot \Delta r)} = \int_{-\infty}^{\infty} f(\Delta r, t)\, \exp\,(i\, k \cdot \Delta r)\, d\Delta r \qquad (10)$$

where $f(\Delta r,t)$ is the distribution of displacements Δr during the time interval τ. Furthermore, the intensity correlation function, which is of physical interest, is related to the field correlation function $R_E(\tau)$ by:

$$R_i(\tau) = I_s^2 + |R_E(\tau)|^2 \tag{11}$$

At this point it is necessary to incorporate the physics of particle movement. For a particle undergoing Brownian motion, the probability of a displacement Δr in a time τ is:

$$f(\Delta r,\tau) = (4\pi D\tau)^{-1/2} \exp\left(- |\Delta r|^2/4\, D\tau\right) \tag{12}$$

where D is the particle diffusion coefficient. The resulting optical spectrum can now be obtained from the intensity correlation function by applying the Wiener-Khinchine theorem:

$$P_i(\omega) = (1/\pi) \int_{-\infty}^{\infty} R_i(\tau) \exp(i\omega\tau)\, d\tau \tag{13}$$

Combining Eqs. (8) through (13) gives the form of the optical spectrum:

$$P_i(\omega) = \frac{E_o^2\, K^2 D/\pi}{(K^2 D)^2 + (\omega - \omega_o)^2} \tag{14}$$

which is a Lorentzian centered at the laser frequency ω_o.

The halfwidth of optical spectrum given by Eq. (14) is measured using homodyne detection. For the case of many particles radiating simultaneously in the focal volume, all frequency components in the broadened optical spectrum are simultaneously incident on the photodetector. The beating of each discrete frequency interval of the optical spectrum with every other discrete frequency interval results in a spectral profile centered at zero frequency, called the homodyne spectrum, which is a Lorentzian function for a monodisperse, stationary aerosol:

$$S_I(\omega) = \frac{I^2}{\pi} \frac{2K^2D}{(2K^2D)^2 + \omega^2} \tag{15}$$

The homodyne spectrum described by Eq. (15) has a halfwidth at half height of $2K^2D$ radians/sec, corresponding to a halfwidth of K^2D/π Hertz.

The particle diameter d in a monodisperse aerosol is related to the diffusion coefficient D by the modified Stokes-Einstein relationship:

$$D = \frac{kT}{3\pi\mu d} C(\ell/d) \tag{16}$$

where the temperature, viscosity and mean free path of the gas are designated T, μ and ℓ, respectively. The effect of mean free path ℓ in Eq. (16) becomes important in the transition flow regime $0.1 < \ell/d < 10$ in which neither continuum nor free molecular drag models apply; the slip correction factor $C(\ell/d)$ is given by Fuchs (1970).

Combining Eqs. (3), (15), and (16), yields a relation for the particle diameter in a monodisperse aerosol:

$$d = \frac{16}{3} \frac{kT}{\lambda^2 \mu} \sin^2\left(\frac{\theta}{2}\right) \frac{C}{HW} \qquad (17)$$

where the halfwidth HW at half height is measured in Hertz. To apply Eq. (17), operating parameters must be selected to minimize the effects of other spectral broadening mechanisms. One of the most serious considerations is the minimization of time of flight broadening (Wang, 1970), which occurs due to the finite duration of the scattered signal from each particle as it traverses the laser beam. The power spectrum of a sine wave of finite duration τ is not a delta function, but has a spectral halfwidth inversely proportional to τ, which corresponds to the particle transit time. The Gaussian spectrum due to time of flight broadening, therefore, has a halfwidth equal to U/2a, where U is the flow velocity, and a is the streamwise Gaussian halfwidth of the optical sampling volume. To apply the DBS technique to high velocity flow fields, the local laser beam diameter a must be increased (thereby sacrificing spatial resolution) to a value such that:

$$a >> U/(4K^2D) \qquad (18)$$

Turbulence and mean flow gradients can also broaden the homodyne spectrum, but their effects can be minimized by insuring that the Doppler shift due to the maximum difference in particle velocities that occur simultaneously in the detection volume is much less than $2K^2D$. Such velocity differences can be reduced by reducing the beam diameter, if necessary.

A basic requirement of the laser light source is that the laser line width be significantly less than the halfwidth of the homodyne spectrum. This requirement is met by conventional helium-neon and argon lasers, for which the linewidth of each longitudinal mode in the laser output is less than 10 hertz. Due to thermal instabilities, the centerline frequency of each longitudinal mode fluctuates and results in a time averaged linewidth of each mode of approximately 10 KHz for helium neon and 10 MHz for argon-ion lasers. These fluctuations have no effect on the homodyne intensity spectrum, which is a result of the beating of different frequency components which must occur simultaneously. Furthermore, multimode laser operation has no affect on the halfwidth of the homodyne spectrum if this halfwidth is less than the laser mode spacing, which is typically 200 MHz.

EXPERIMENTAL CONDITIONS

One inherent advantage of the use of the DBS technique is the simplicity of the experimental system, making it especially attractive for use in hostile environments. Scattered radiation from a single laser beam is collected at a selected scattering angle and measured using a photomultiplier tube. The power spectrum of phototube current fluctuation is then measured using a conventional spectrum analyzer or by the photon correlation method (Cummins and Pike, 1973).

A schematic of the experimental configuration used in this study is shown in Fig. 1. A 28 milliwatt helium neon laser was used with a beamsplitter to provide two beams of equal intensity which were focussed to intersect at the sampling location. This arrangement allowed scattered radiation to be observed at either a 25° or 60° angle from the incident beam using fixed detection optics, by alternately blocking one of the beams. Local beam diameter was 1 mm. A collecting lens of 15.2 cm focal length was used to focus the enlarged (3X) image of the focal volume on the surface of an RCA 4832 photomultiplier tube. An interference filter centered at 632.8 nm with a measured halfwidth of 1.6 nm was used to filter out flame emission. Photomultiplier current was passed to ground through a .1 MΩ resistor, providing a photctube frequency response of 50 KHz.

Scattered laser radiation from flame particulates was visually observed through a pinhole drilled in the back wall of the phototube mount, and proper focus was obtained when the entire collection lens (i.e. detection solid angle) was filled with scattered laser light. The ratio of signal to flame emission was measured to exceed 25 and the measured ratio of signal to shot noise was greater than 40.

A flat flame laboratory burner was used in this study which consisted of a core of bundled copper rods between which flowed premixed acetylene, oxygen and a nitrogen dilutant introduced to vary flame temperature and thus flame speed.

The 3.18 cm diameter burner surface was recessed and surrounded by an annular flow of nitrogen, which considerably aided flame stability. The entire apparatus was water cooled. Unburned gas velocity was determined using a flowmeter to be 20 cm/sec at a fuel air equivalence ratio $\phi = 2.5$.

The measured flame emission was relatively steady, with $\pm$ 10% variations at frequencies of 5-15 Hertz. The intensity of scattered laser light was unsteady due to time varying aerosol concentrations. However, unsteady aerosol conditions pose no fundamental limitations to the sizing technique since all signal fluctuations of frequency less than 1 KHz were later removed by filtering during the data reduction.

Fluctuations in the phototube current were recorded on analog tape using an AMPEX 1200 FM recording system and analyzed using a digital spectrum analyzer (Spectral Dynamics 360-35). This unique instrument displays the time averaged power spectrum as recorded data is continuously digitized and Fourier transformed. Data was first high pass filtered at 1 Khz and digitized at sampling rates of 16 - 32 KHz. Each computed spectrum was determined from 2.5×10^5 data points.

PARTICLE SIZE DETERMINATION

The size of particles in the acetylene-oxygen flame was determined from measured homodyne spectra using Eq. (17). An example of a filtered spectrum is shown in Fig. 2. The half-width (HW) of the Lorentzian homodyne spectrum is related to the filtered spectrum by the relation:

$$HW^2 = f_{HM}^2 - 2f_o^2 \qquad (18)$$

where f_{HM} is the frequency in Hertz at which the intensity spectrum has decreased to half the maximum measured value, and f_o is the high pass filter frequency, which in this case was 1 KHz.

Flame temperature and concentration of 26 combustion species were calculated using the AFRPL-ISP computer routine, which utilizes updated JANNAF thermochemical rate constants. For $\phi = 2.5$, a flame temperature of 2250°K was calculated, resulting in a value of μ of 6.72×10^{-5} j sec/m^3 and a value of ℓ of 350 nm. Results of particle sizing measurements are shown in Fig. 3 for various heights above the flat flame burner, scattering angle θ, and fuel air equivalence ratio ϕ.

DISCUSSION

The results shown in Fig. 3 are encouraging because they indicate that Diffusion Broadening Spectroscopy can be applied in a straightforward manner to determine particle sizes in flames. Measured particle diameter is observed to increase from 40 nm to 260 nm as the height h above the flame front increases from 0.5 cm to 3.0 cm. This trend is consistent with the fact that as h increases, particle residence time increases and the probability of particle agglomoration increases. No definite effect of equivalence ratio on particle size was observed. Initial particle formation was believed to occur at a location h = 0.1 cm, as evidenced by

broadband visible radiation in that region. However, the ratio of signal to flame emission was less than 10 in the region h = 0.1 to 0.5 cm. It was therefore concluded that in order to determine particle size in the size range below 40 nm in this flame, it is necessary to either provide laser power in excess of 28 milliwatts or to reduce the bandwidth of the optical system to less than 1.6 nm.

Laser power requirements for flame studies are dictated by particle concentration and size, flame emission intensity, and the detection optics. As particle size decreases, the intensity of Rayleigh scattered light decreases as d^6, while broadband flame emission only decreases as d^2, eventually necessitating the use of higher laser power or improved optical filtering. The ratio of scattered signal to flame emission can be calculated from:

$$\frac{S}{N} = \frac{P_o}{A_o} \frac{16\pi^4 d^6}{\lambda^4} \left(\frac{m^2 - 1}{m^2 + 2} \right)^2 (1 + \cos^2 \theta) / (\varepsilon \, R(\lambda, T) \, d^2 \, \Delta\lambda) \quad (19)$$

where P_o is the laser power, $\Delta\lambda$ is the bandwidth of the optical system, A_o is the local laser cross section area, m and ε are particle index of refraction and emissivity, respectively, and R is the Planck function in watts/cm^2 μm.

The effects of other spectral broadening mechanisms were assessed by varying the scattering angle θ. Diffusion broadening is the only mechanism that has a θ dependence, and Eq. (17) predicts that the ratio of halfwidths measured at θ equal to 60° and 25°, respectively, for a monodisperse aerosol is 5.33.

The measured ratio HW (60°)/HW (25°) was found to be 4.2 at location y = 1 cm and ϕ = 2.5. The large θ dependence measured in this study therefore indicates that the primary broadening mechanism is diffusion broadening. Time of flight broadening was calculated to be less than 0.7 Khz. Furthermore, the deviation of the above result from that predicted by Eq. (17) for a monodisperse aerosol is used later to estimate the particle size distribution function.

An electron microscope was also used to size the carbon particulates, using a Nichrome wire to obtain samples at 3 cm above the burner. A typical electron micrograph is shown in Fig. 4. Particulates were observed to be in the 200 nm range, in agreement with the results of Fig. 3.

← Fig 4

SIZE DISTRIBUTION MEASUREMENTS

It is reasonable to ask two questions concerning the use of Diffusion Broadening Spectroscopy in polydisperse aerosols. First, what does the mean diameter determined from Eq. (17) represent? Secondly, is it possible to deduce the particle size distribution parameters? To assess the effects of polydispersity, consider an aerosol whose size distribution function n(d) is composed of N discrete size components. The resulting diffusion broadened homodyne spectrum is the arithmetic sum of N^2 simple Lorentzians, given by:

$$S = \frac{A}{\pi}\left(\frac{P_o}{A_o}\right)^2 \sum_j \sum_k \frac{\sigma_j \sigma_k n_j n_k K^2 (D_j + D_k)}{[K^2 (D_j + D_k)]^2 + f^2} \qquad (20)$$

where A depends on the optical geometry, and

where σ_j and σ_k are the Mie scattering cross sections corresponding to jth and kth particle diameters, respectively. In addition to N Lorentzians (one for each size component), Eq. (20) includes N^2 - N cross beat terms which result from beating between optical spectra that correspond to the jth and kth size components.

To assess the effects of polydispersity, a computer routine was developed to evaluate Eq. (20). A log-normal particle size distribution was used, which was characterized by a geometric mean diameter dg and a geometric standard deviation s. Mie scattering cross sections of carbon particles are given by Fenn (1966). Senftleben and Benedict (1919) have measured the index of refraction of carbon particles to be m = 1.59 - 0.66i. Computer calculations were performed with gas conditions and scattering angles equal to value corresponding to the flame study.

Results are shown in Figs. 5, 6, and 7. The measured halfwidth in Fig. 5 is strongly affected by the degree of aerosol polydispersity. The weighted mean diameter d_m obtained from Eq. (17) is therefore not a good estimate of geometric mean diameter. However, Fig. 6 shows that the value of d_m calculated from Eq. (17) is a fairly good estimator of the surface mean diameter. This result means that a reasonable estimate of surface mean diameter can be determined in polydisperse carbon aerosols simply by using Eq. (17). A similar result was obtained by Hinds and Reist for nonabsorptive

← Fig 5, 7

particles for which m = 1.52. In both cases the correlation obtained is an empirical result and may not be valid for particles of a different index of refraction.

A method to measure the size distribution parameters is now proposed. For the case of carbon particles, our results show that measurements of homodyne spectral halfwidth at two angles is sufficient to determine size distribution parameters dg and s. Optimum sensitivity is obtained by properly choosing the two scattering angles. In effect we are combining the DBS technique with well-known Mie scattering principles.

Figure 7 indicates the range and limitations of size distribution measurements. The measured halfwidth ratio is seen to be adequately sensitive to variations in the value of s in the range $dg > .025$ μm and $s > 1.5$.

The poor sensitivity of the .01 μm curve in Fig. 7 is due to the fact that the scattering cross section is no longer angular dependent in the Rayleigh scattering regime ($d < \lambda/10$). In the Rayleigh regime, all of the Lorentzians in Eq. (20) are broadened equally and amplified equally by a factor of $\sin^2 \theta/2$. Our computer model verified that the resulting spectrum is broadened exactly by $\sin^2 \theta/2$ and that the degree of polydispersity cannot be deduced for $d < .01$ μm for our conditions. Adequate sensitivity and the single valued nature of the curves in Fig. 7 are due in part to the relatively well behaved nature of the Mie cross section for carbon; this may not be true for nonabsorbing particles.

Values of dg and s can be deduced directly from Figs. 6 and 7. Measured values of halfwidth and halfwidth ratio correspond to horizontal lines on each graph. Values of dg and s are then deduced visually by iteration. For example, data obtained at h = 1 cm in the acetylene/oxygen flame used in this study corresponds to HW (60°) = 8.1 KHz and HW (60°)/ HW (25°) = 4.2. The deduced value of dg is .105 $\pm$ .03 μm and s = 1.5 $\pm$ .2. Relatively large uncertainty results in this case from the double valued nature of the curves in Fig. 7 over a small range of conditions.

- - - - - -

~~The~~ Experimental research reported in this paper was performed at the Air Force Rocket Propulsion Laboratory, Edwards, California; funds were made available by the Air Force Office of Scientific Research and administered by Auburn University under the 1977 USAF-ASEE Summer Faculty Research Program. Other funds were made available through AFOSR grant AFOSR78-3556.

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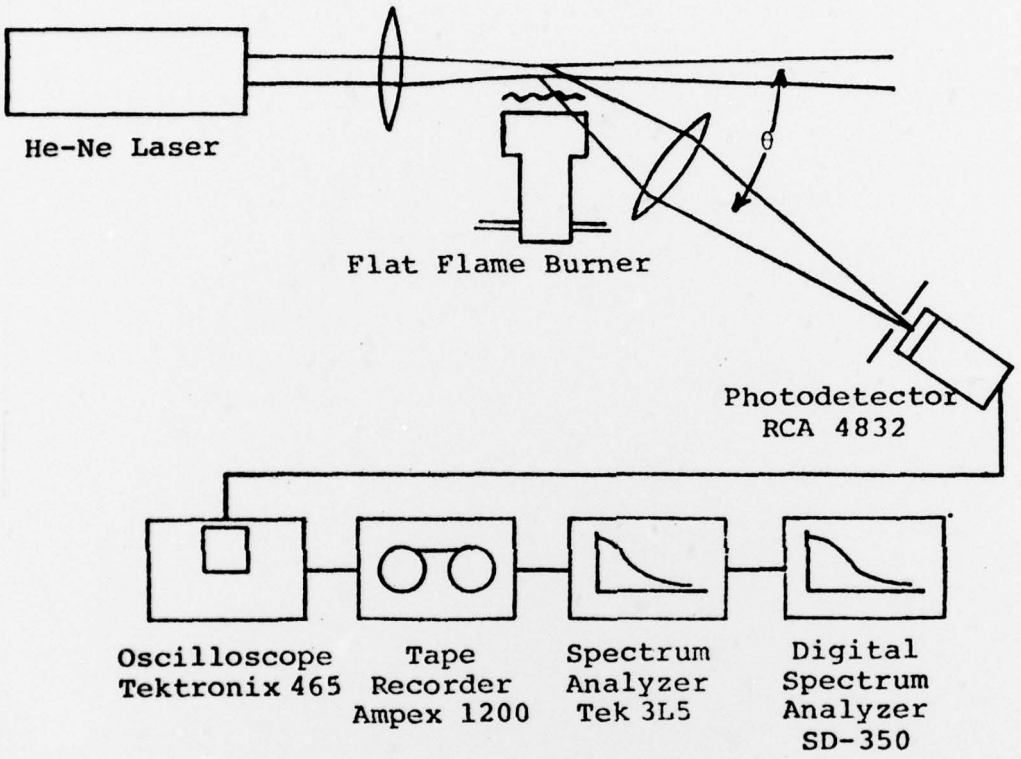


Figure 1 Brzustowski, J. F

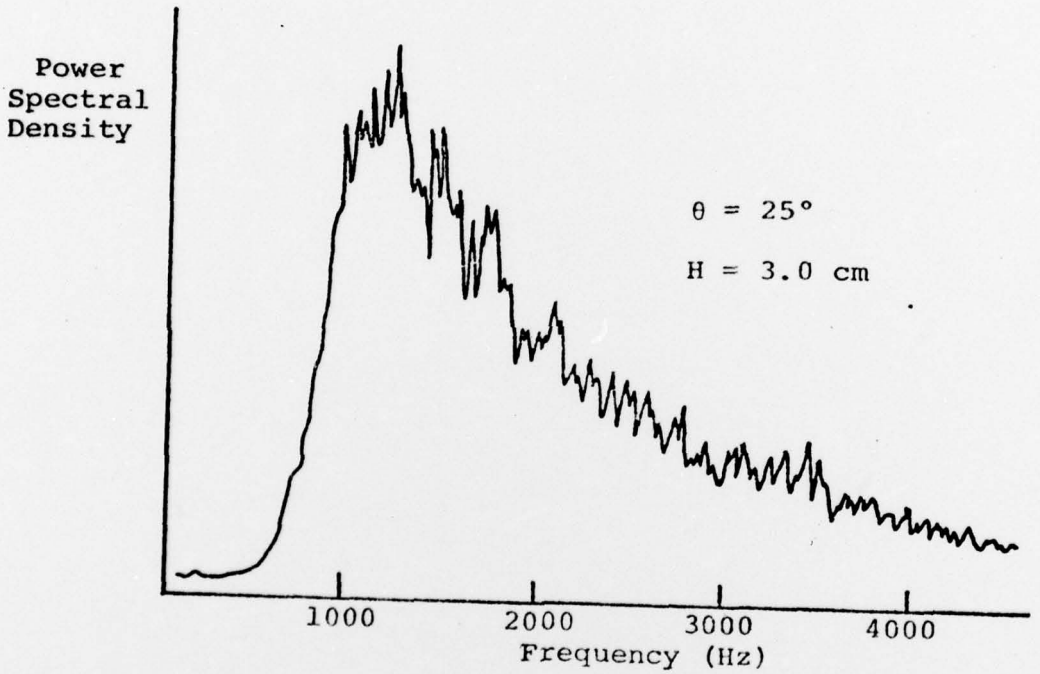

Power
Spectral
Density
θ = 25°
H = 3.0 cm
1000
2000
3000
4000
Frequency (Hz)

Fig. 2

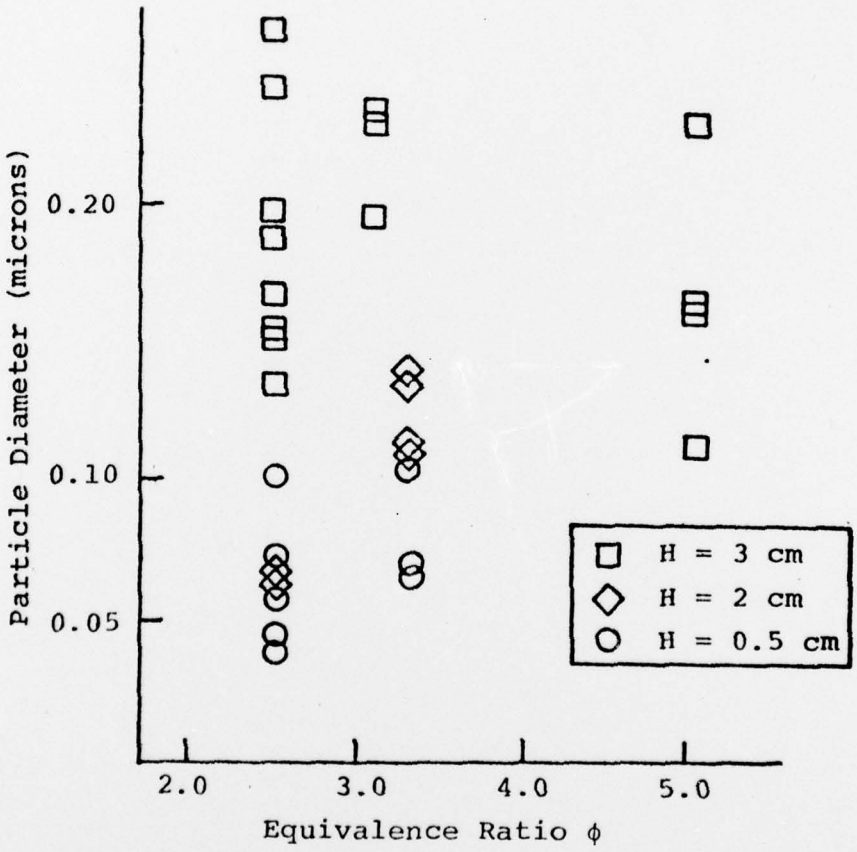
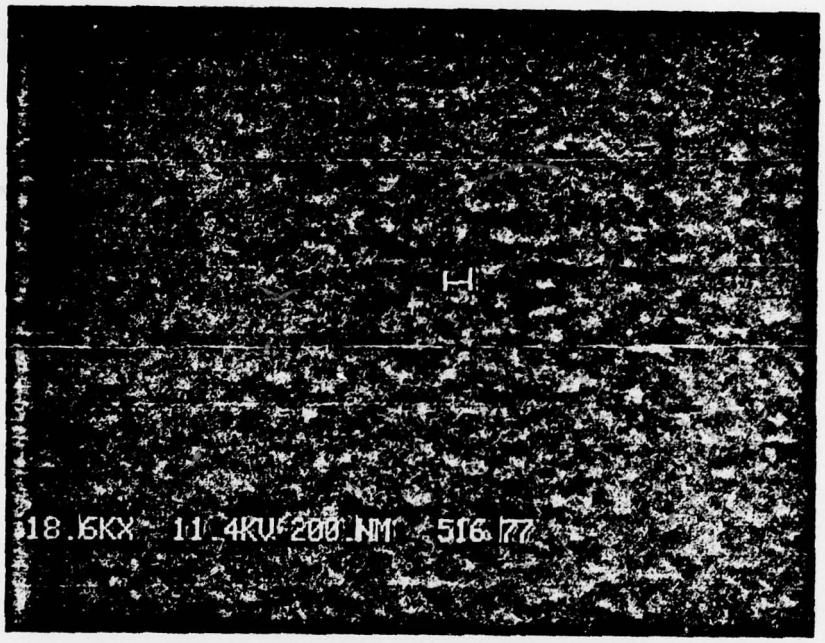


Fig. 3 Diameter


18.6KX 11.4KV 200 NM 516 77

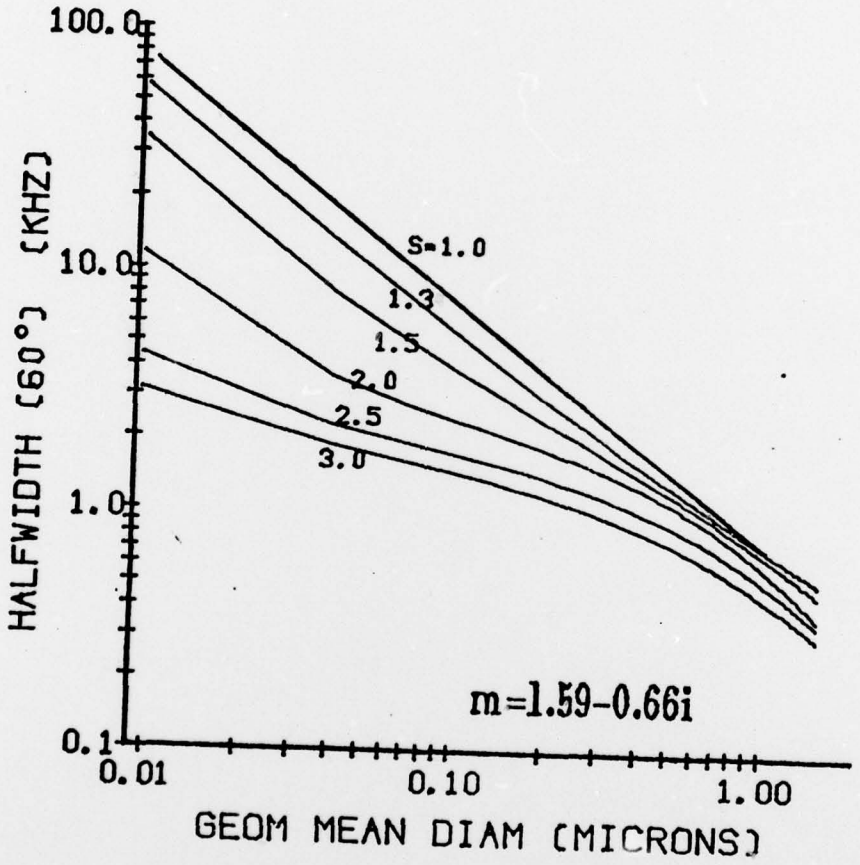

100.0
10.0
1.0
0.1
HALFWIDTH (60°) (KHZ)
S=1.0
1.3
1.5
2.0
2.5
3.0
m=1.59-0.66i
0.01
0.10
1.00
GEOM MEAN DIAM (MICRONS)

Figure 5

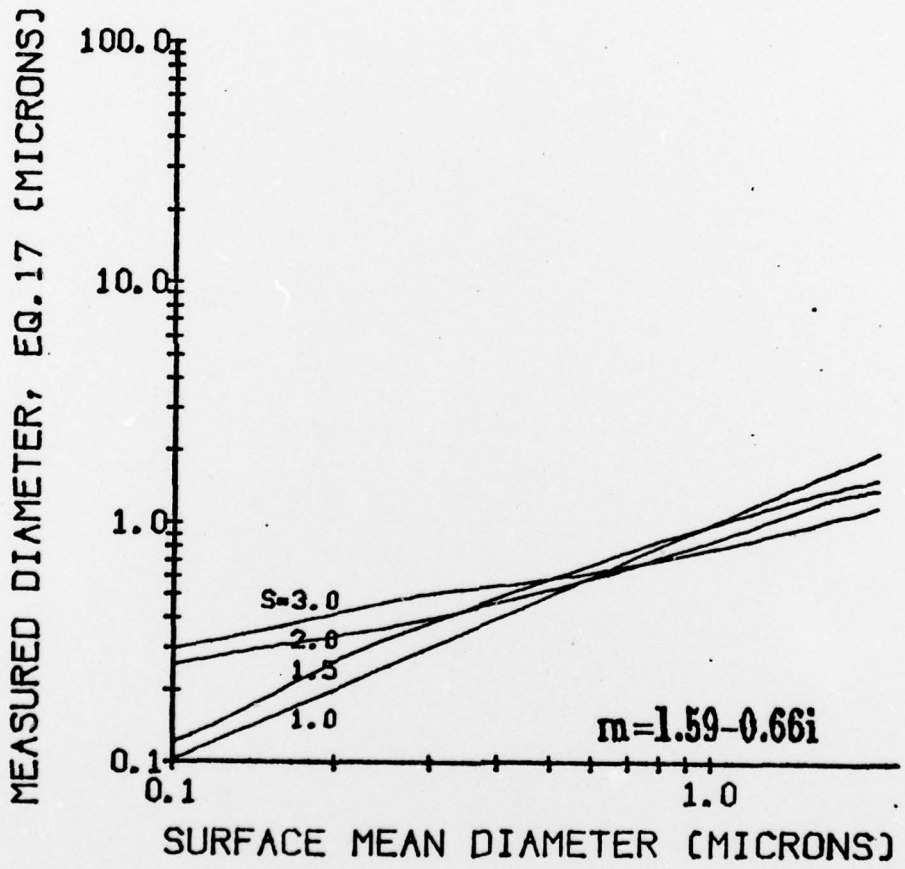


Figure 6 Driscoll, Sauer F

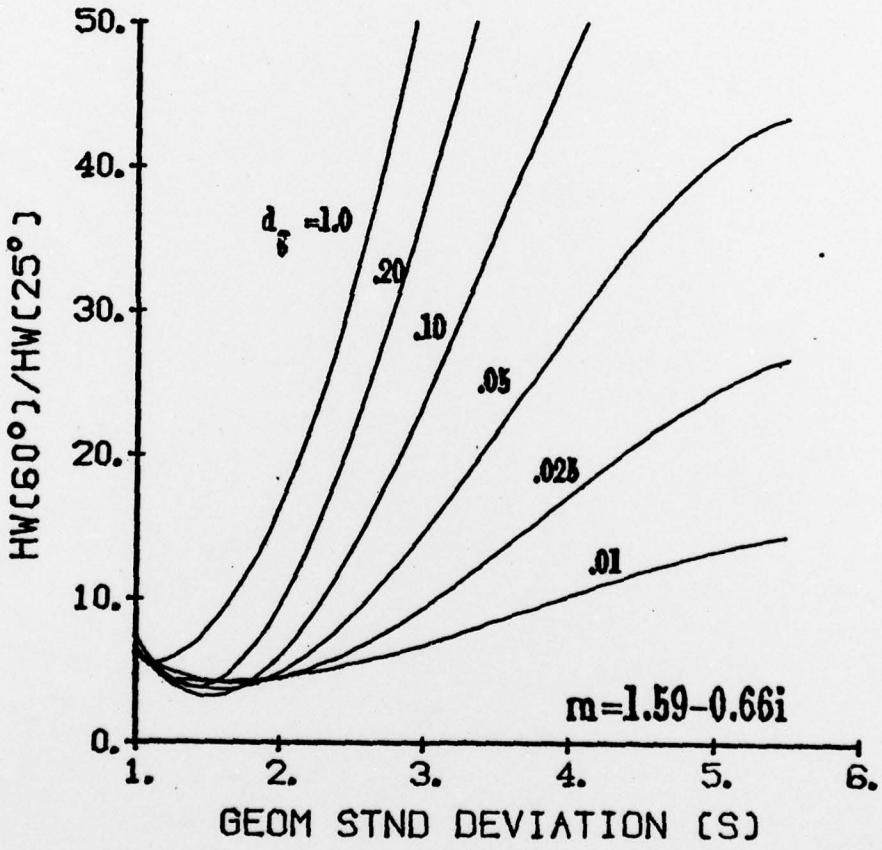


Figure 7 Draw all, James F

FIGURE CAPTIONS

Figure 1. Schematic of Experimental Arrangement

Figure 2. Measured Power Spectrum in an Acetylene-Oxygen Flame ($\theta = 25°$, H = 3.0 cm)

Figure 3. Particle Diameters Measured in an Acetylene-Oxygen Flame

Figure 4. Electron Micrograph of Flame Particulates Sampled at H = 3.0 cm (Indicator Width = 0.2 μm)

Figure 5. Sensitivity of Measured Spectral Halfwidth to Geometric Mean Diameter for a Polydisperse Carbon Aerosol

Figure 6. Correlation of Measured Diameter [Eq. (17)] with Surface Mean Diameter

Figure 7. Sensitivity of Spectral Halfwidth Ratio to Geometric Standard Deviation in a Polydisperse Carbon Aerosol